MicroFlyers and Aerial Robots
Missions and Design Criteria

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Summary
This paper provides an overview of the issues surrounding the design and choice of appropriate missions for a new class of unmanned flying vehicles known as MicroFlyers, Micro Air Vehicles, and Aerial Robots. These terms are often used interchangeably to refer to small flying machines varying from what amounts to "intelligent dust" up to vehicles in the size range of small radio-controlled models (i.e., having a typical maximum dimension of one meter). Because of the size of this class of air vehicle, it can engage in missions that are non-traditional, such as indoor flight through confined spaces, or en mass, to overwhelm a target in swarms. Also because of size, many of these vehicles will have to be autonomous. In some cases, the design of the vehicle will benefit from biological mimicry wherein the behavioral and locomotive techniques used by birds and insects will be of advantage. However, the small size of these air vehicles will also constrain them in the physical environment in much the same way that insects are not necessarily free to navigate at will in the presence of wind and precipitation.

NOMENCLATURE

Aerial Robot	*Intelligent, Autonomous UAV*
Entomopter	*Insect-Like Biomimetic Aerial Robot*
MAR	*Mesoscaled Aerial Robot*
MAV	*Small (<15 cm) UAV or RPV*
MicroFlyer	*Small (<20 cm) Aerial Robot*
MEMS	*Microelectromechanical Systems*
RCM	*Reciprocating Chemical Muscle*
RPA	*Remotely Piloted Aircraft*
RPV	*Remotely Piloted Vehicle*
UAV	*Unmanned Aerial Vehicle*

Autonomous Navigation
Not all unmanned aerial vehicles need to be autonomous, but autonomy is one thing that Aerial Robots and MicroFlyers have in common. Not only must they be able to maintain stability in flight– the difficulty of which is somewhat a function of the air vehicle configuration, but they must be able to navigate. Aerial Robots, can navigate with the aid of various standards ranging from star trackers to geographical cues to man-made aids. The class of Aerial Robots known as MicroFlyers which may operate indoors, can not necessarily access these traditional standards, and without a priori knowledge of the environment, must rely on less structured approaches to self navigation.

Navigation is the process by which one determines the best route from one location (often one's present position) to another location. The easiest method for navigating about one's environment involves moving between line-of-sight landmarks or by following paths (such as rivers) which are known to lead to the desired location. When moving through unknown territory, or regions devoid of stationary landmarks, these techniques fail and specialized tools must be employed to find one's way. Navigation tools relying upon the relative position of celestial bodies or the direction of a load stone-magnetized iron sliver floating on water provided early travelers with the ability to maintain a course over long distances. In time, sophisticated artificial land marks capable of being sensed electronically allowed the traveler to circumnavigate the globe regardless of the time of day and under all weather conditions.

Modern navigation tools use man-made constellations of ground or space-based standards which emit electromagnetic waves of known frequency, phase,

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or encoding to provide a local receiving device anywhere in the world with an estimate of its position relative to these standards. Depending upon the system configuration, coordinates on or above the Earth's surface can be determined within centimeters of the actual position. In general, these systems rely on the ability to accurately measure qualities of signals emitted from at least three sources of known position. The accuracy of the triangulated position solution is also a function of geometry, with the most accurate solutions being derived from signal sources surrounding one's current position (as opposed to signals received from sources along a line).

Some of the popular ground-based systems currently in use are VOR (**V**ery High Frequency **O**mni **R**ange) used predominantly for regional aircraft navigation, and LORAN (**Lo**ng **Ra**nge **N**avigation) which is used by both ships and planes globally. Many such systems have been deployed over the years as aids to navigation, but with the advent of the highly accurate space-based Global Positioning System (GPS), more of these ground-based systems are being decommissioned (e.g., OMEGA).

Autonomous Navigation

There are some scenarios in which the classical navigation aids are not readily available either because their signals can not be received, or because the triangulation calculations used to compute a position contain too great an error to be of use. Even if the navigation aids are available and meaningful results can be obtained, absence of human input to the navigation process can be challenging. Consider the following actual examples.

A Mars probe lands in the caldera of the Solar System's largest volcano, Olympus Mons. Scientists wish to have the probe map the caldera by deploying a small aerial robot that will fly a grid pattern across the base of the caldera while taking photographs at the grid intersections. How will the aerial robot know where it is? The magnetic field of Mars is very weak, there is no ground-based or orbital standard emitting signals by which to triangulate a position, the terrain is unfamiliar and precludes the use of landmarks.

A second example would be a MicroFlyer operating inside a building. Though GPS signals are available just outside the building— perhaps only feet away, the signal is effectively blocked by the materials used in the construction of the walls and ceiling. Compounding matters, the MicroFlyer is a flapping wing design mimicking insect locomotion and has a maximum dimension of only 12.7 centimeters (5 inches) and a weight of 50 grams (1.76 ounces) [see, http://avdil.gtri.gatech.edu/RCM/RCM/Entomopter/EntomopterProject.html]. The wavelength of the GPS satellite signals would require an antenna that is as big as the entire MicroFlyer. Without a priori knowledge of the building interior, how could such a tiny reconnaissance vehicle find its target?

In both examples, such vehicles are currently under development. The first suffers from a lack a accurate navigation aids while in the second case, though navigation signals are present and adequate, they are unable to be detected due to occlusion and the inability of a receiving antenna to be scaled to a size and weight that is compatible with this specialized vehicle. Both example vehicles are candidates for autonomous navigation.

Autonomous navigation means that a vehicle is able to plan its path and execute its plan without human intervention. In some cases, remote navigation aids can be used to help in the planning process, while at other times, the only information available to compute a path is based on input from sensors that are local to the vehicle itself. An autonomous robot is one which can not only maintain its own stability as it moves, but can also plan its movements. Autonomous robots use navigation aids when possible, but can also rely on vision, auditory, and olfactory cues. Once basic position information is gathered in the form of triangulated signals or environmental perception, machine intelligence must be applied to translate some basic motivation (reason for leaving the present position) into a route and motion plan. This plan may have to accommodate the estimated or communicated intentions of other autonomous robots in order to prevent collisions, while considering the dynamics of its own movement envelope.

Basic Principles of Autonomous Navigation

Autonomous navigation is advantageous for some mobile robotic missions— it is essential for others. In some cases, the presence of a manned vehicle is a liability because regard for life precludes engagement in missions that are lethal. Flying into nuclear contaminated areas to make measurements is one example of a mission that is better left to an unmanned system. Even the presence of a man-in-theloop is often a disadvantage. Remotely piloted reconnaissance vehicles that are flown by means of a ground pilot and a command/data link are susceptible to jamming, deception, or being overridden by the enemy. An autonomous vehicle requires no command links and therefore is unstoppable by jamming or overriding, and the ground pilot can not be deceived by modifying the feedback information to that is normally returned by a data link. Autonomous vehicles are superior for many tasks but the challenge to make the vehicle navigationally robust in all situations, is formidable.

For an autonomous vehicle to be navigationally robust it must be capable of six things:

1) It must have a mission goal (motivation to move),
2) It must be able to perceive its environment (for obstacle avoidance),
3) It must understand where it is presently located,
4) It must plan a path that will allow it to achieve its goal,
5) It must be self actuating (able to move), and additionally,
6) as situations change, it must be able to replan as it moves.

Sensors for Autonomous Localization and Navigation

Before an autonomous vehicle can intelligently plan a path to its goal, it must either have a stored map of its world, or it must create one as it moves based on what it perceives. In the case of the autonomous insect-like MicroFlyer, a map of the interior of the building in which it will fly would be of significant use, but even with such a map stored onboard, furniture and other unbriefed threats to the vehicle could block its path. In most cases, such a map will not be available and the MicroFlyer would have to sense the path to its target based upon other cues.

Knowing What is Up

In most systems, particularly those used in flying robots, it is critical to know where "up" is. In an aerial robot, knowing the orientation of the vertical gravity vector allows the vehicle to remain in flight parallel to the surface of the Earth, or to return to that orientation after completing a maneuver. Knowing where "up" is can also affect the calibration of various onboard sensors. Accelerometers are affected not only by changes in robot velocity but also by orientation relative to the gravity force vector which must be factored out of any measurements. Similarly, magnetometers used to determine heading rely on the measurement of only the horizontal component of the Earth's magnetic field vector. If an aerial robot with electronic compass such as a flux gate magnetometer banks in a turn so that the compass tilts relative to a plane that is tangent to the Earth's mean surface, the compass will begin to read not only the horizontal component of the Earth's magnetic field, but also part of the vertical component. In the northern hemisphere, this will result in an erroneous heading that is biased to the North. The magnetic field of the Earth can be resolved for any vehicle attitude by using three redundant magnetometers in an orthogonal array, but in order to select only the horizontal component of this vector, some knowledge of "up" is necessary to determine where the horizontal plane lies.

"Up" can be measured by a pendulum, and electronic pendulums comprised of accelerometer arrays do exist. However these are not reliable on a moving platform. An aerial robot capable of performing a coordinated banking turn would temporarily create artificial gravity due to centrifugal "force" and a pendulum would indicate that the vehicle is still flying straight and level. For this reason vertical gyroscopes are often used to remember where "up" is. A vertical gyroscope is gimballed to allow its spin axis to freely rotate about its spin center. As such, a vertical gyroscope can indicate offsets in yaw, roll, and pitch relative to its calibrated starting position if placed at the center of rotation (often the center of gravity) of an autonomous aerial robot. This starting position is usually the vertical gravity vector as derived from a pendulum sensor when the vehicle is at rest. Unlike the pendulum however, a properly placed vertical gyroscope is not affected by centrifugal "force".

Vertical gyroscopes can be simulated by twice integrating the output from orthogonal accelerometers, or from a single integration of orthogonal rate gyro outputs. Relatively accurate vertical gyroscopes can thus be created by integrating the output of orthogonal laser ring (rate) gyros.

Detecting "up" is one of the most important abilities exhibited by autonomous terrestrial robots, and is likewise one of the most difficult quantities to obtain. Once "up" has been determined, cumulative errors eventually corrupt the robot's notion of where "up" actually is. Vertical gyroscopes exhibit very good accuracy in the short term, but are subject to drift. For this reason sensors with good long term stability but lower update rate are often coupled with vertical gyroscopes to periodically recalibrate them. For example, GPS position fixes can be very accurate but update rates from 1 to 10 Hz are too slow to meet the needs of autonomous robots engaging in high rate-of-change maneuvers. However, GPS position updates can be used to correct angular drift errors occurring in otherwise highly responsive vertical gyroscope systems. This synergy provides sufficiently accurate high bandwidth feedback for an autonomous control system to direct the dynamic envelope of most mobile robotic platforms.

Route and Motion Planning

If a global map is available, an autonomous vehicle can plan its entire route from its present position to its goal. Some route planners search for the optimum path based on rules which attempt to minimize transit time, fuel consumption, threat exposure, or other factors. Thousands of routes are planned based on way points, and the one best conforming to the mission rules is chosen. As the path is executed, unbriefed threats which would cause the autonomous vehicle to violate the mission rules may be encountered and the route must be recomputed from the vehicle's current position. Under some circumstances no solution is possible in which case certain rules must be relaxed. For example, a higher degree of threat exposure may be acceptable, however other rules may be inviolate such as those concerning mission endurance. A route requiring the vehicle to exceed its remaining fuel allotment is obviously an unacceptable alternative. Therefore, unless the robot is expendable, provision must be made for autonomous vehicle to abort its mission and return home.

A more rigorous case is one in which no global map is available. In this case, the optimum route can not be predicted, and a combination of dead reckoning and seek/avoid behaviors must be used. Dead reckoning uses time-in-motion at a certain speed along a given heading to extrapolate a new position based on a known starting point. Odometry is a form of dead reckoning often used in factory robots to count the revolutions of a drive wheel of known circumference in order to determine distance traveled independent of time. Visual odometry is also possible from aerial robots in which the passage of objects on the ground is noted. By knowing the altitude of the aerial robot and the field of view of its vision sensor, a measure of distance traveled can be deduced.

Dead reckoning is plagued by cumulative errors which arise from inaccuracies in the measurement of time, speed, and heading. These may be due to the inherent resolution of the sensors used, or my be due to drift caused by unpredictable changes in the environment. Dead reckoning errors grow as the mission progresses unless there is some standard to periodically recalibrate the absolute position of the vehicle. Dead reckoning sensors include devices such as accelerometers (to measure acceleration), rate gyroscopes (to measure rate of change of velocity), and magnetometers (to measure heading). By integrating acceleration, one can determine velocity, and by integrating velocity, one can determine position. The use of laser ring gyroscopes or accelerometers based on microelectromechanical systems (MEMS) components can increase the accuracy of dead reckoning systems.

Seek/avoid systems on the other hand, are as accurate as the resolution of the sensors used to seek the goal. Unlike dead reckoning, accuracy improves as the seeking sensor is brought nearer to its goal because the error signals provided by the sensor are greater for smaller vehicle heading deviations when near the target than when far from it. Larger error signals are less susceptible to noise, and the heading can be maintained more accurately.

The avoidance signal serves as a warning to override the seeking behavior when a threat to the vehicle is encountered. After successfully diverting from the desired seeker path by changing heading or altitude to avoid a detected obstacle by means of a preprogrammed (reflexive) or calculated (cognitive) maneuver, the avoidance sensors no longer detect the obstacle and control is returned to the seeking sensors whereupon the robot continues toward its goal on a new path.

Consider a mission in which a tiny autonomous air vehicle is launched through an air vent from the outside to search for the location of hostages being held somewhere in an abandoned building. In this example, no recent map of the interior is available, though intelligence reports indicate that the building has a group of central rooms accessible by hallways off of a main corridor. In this case a reasonable sensor suite would include ranging devices to avoid obstacles in front of, and to the sides of the vehicle. In addition a downward looking ranging device would provide altimetry information.

These could be active radio frequency, optical, or acoustic transceivers similar to radar or sonar and would only serve to keep the vehicle out of harm's way during its ingress.

Another kind of sensor would be used to provide motivation. This might be an "electronic nose" which detects small quantities of molecular species that indicate the presence of human beings. Pheromones, ammonia, or other chemicals given off by humans could be used as a cue to lead the autonomous vehicle toward its goal in much the same way that a blood hound seeks a target based on smell. A pair of molecular sensors placed on either side the MicroFlyer's "head" could then indicate that concentration of the target molecules is greater to the right, left, or if equal— straight ahead. Thus, a motivation to move in a particular direction is provided.

The MicroFlyer Mission

Given that a UAV can be made to fly stably, and autonomously navigate, where might such a device be used? Many missions for MicroFlyers have been proffered, but all basically fall into the categories of "outdoor", "urban", and "indoor". The domain for MicroFlyers will be as key elements of indoor missions. Major, and perhaps insurmountable obstacles confront MicroFlyers that fall prey to the forces of the environment. Wind and rain can prevent outdoor MicroFlyer flight from taking place as the tiny air vehicle could expend its entire energy store getting nowhere in an attempt to fly at 20 kph in a 20 kph head wind. Similarly, rain will not only attenuate signals from the necessarily high frequency command links but may even push the tiny craft to the ground. Besides, assets exist for most outdoor reconnaissance missions– why use a MicroFlyer?

Proponents would argue that MicroFlyers put the reconnaissance potential in the hands of the users that need specific information in a timely manner. Perhaps a better solution would be to invest in networked communications systems that can get the same information to the foot soldier in a timely manner from existing unmanned aerial vehicle (UAV) assets such as Predator or the Global Hawk. Global Hawk will look over *all* hills in the theater of war, providing continuous 0.09 square meter (1 square ft) resolution views of the ground from an altitude of 20 km (65,000 ft) for periods of up to 36 hours! Multiplexing the Global Hawk sensors to take snap shots of specific regions of the battlefield and to deliver them to individual users on the ground in near real time is probably an easier and better integrated approach to C^3I than the anarchy of hundreds of tiny personal eyes in the sky careening at the mercy of the wind.

Urban settings, where the next generation of conflicts are predicted to occur, present difficulty for existing UAV assets. This is because most UAVs are fixed wing vehicles and are too fast to negotiate the urban canyons. Flying high over a city is of use, but if one could gather reconnaissance down in these urban canyons– between buildings, then a greater situational awareness could be had. MicroFlyers are a reasonable candidate for this mission since they are smaller and potentially slower than conventional UAVs. Even fixed wing MicroFlyers could conceivably negotiate city streets, but MicroFlyers capable of slow flight and even hover would afford the ability to stop, look into windows, or even land in tight spaces to place sensors. On the other hand, wind and rain will still plague these tiny air vehicles, and the occlusion of signals by buildings will exacerbate communication and navigation.

The real mission niche for MicroFlyers will be indoors where the environment is controlled, and there are *no* existing airborne reconnaissance craft that can negotiate hallways, crawl under doors, or navigate ventilation systems in an attempt to complete a reconnaissance mission. It is the indoor mission that will ultimately justify the development expense. The very nature of an indoor mission will necessitate (1) multimode vehicles (flying/crawling/rolling), and (2) autonomous navigation. These two features of an indoor MicroFlyer are not absolutely necessary for outdoor missions, but outdoor MicroFlyer missions are themselves not absolutely necessary. Therefore, investment in the design of autonomous multimode MicroFlyers which incorporate these features from the inception of their design is paramount.

Morphology of a MicroFlyer

Nothing in creation exhibits fixed wing flight behavior or propeller-driven thrust. Everything that maintains sustained flight, uses flapping wings. Even though there has been considerable analysis in the literature of mechanisms for bird flight (Ellington[1], 1984) and insect flight (e.g., Azuma[2], 1992, and Brodsky[3], 1994), and ornithopter-based (bird flight) machines have been demonstrated–

nothing at the size level of an entomopter (GK: *en*, in + *temnein*, to cut (in ref. to an insect's segmented body) + *pteron*, wing → "insect wing") has been tried.

An entomopter, or robotic insect, capable of self navigating indoor flight and ground locomotion using a "reciprocating chemical muscle" technique is currently under development by a team of U.S. and European researchers[4] with funding from the U.S. Defense Advanced Research Projects Agency (DARPA). This particular MicroFlyer is referred to as a Mesoscaled Aerial Robot (MAR).

Major Hurdles

Beyond the challenges of low Reynolds number aerodynamics (*inertial force of body ÷ viscous force of air*), three major system-specific technological areas must be addressed before a any practical MicroFlyer can be fielded. These are:

- NONSCALING ITEMS
- STORED ENERGY
- PROPULSION

NONSCALING ITEMS may be functions of external factors such as established GPS frequencies over which there is little control. For example antennas may be of suboptimal gain or directivity in order to fit the form factor of a MicroFlyer, while ground station frequencies may of necessity, preclude anything but line-of-sight operation. A reconnaissance MicroFlyer operating line-of-sight at a distance of several kilometers may require an operational altitude of several thousand feet in order to clear tree lines, hills, and cultural items. The cost of being small becomes of questionable benefit when the mission envelope begins to overlap that of existing assets which can perform the same reconnaissance mission.

STORED ENERGY becomes a significant impediment as MicroFlyer mission duration increases. The present state-of-the-art in battery technology does not allow for long endurance MicroFlyer missions, though it is hoped that someday improved electrical storage media (carbon-air, fuel cells, etc.) will result in the energy densities required for useful long endurance (> 1 hour) missions in MicroFlyer-sized vehicles. Near term solutions to onboard energy storage will come from chemical or fossil fuels because of their superior energy density. As a point of comparison, consider the amount of releasable energy stored in a drop of gasoline compared to that which can be stored in a battery the size of a drop of gasoline.

Given that a high energy fuel source is used, the third system-specific technological area which must be addressed is PROPULSION, that is, how one converts the fuel's stored energy into useful, controllable work. This involves some sort of engine, and a propulsor system. The approach described in this paper is to use a chemical fuel source driving a specialized scalable engine known as the "reciprocating chemical muscle" (RCM), coupled to flapping wing propulsors. This combination is deemed to be optimal for indoor MicroFlyer missions where the MicroFlyer is more than a simple flying machine, but a robot capable of demonstrating various insect-like behaviors including the ability to land, crawl, and take off again.

Models for Beginning a MicroFlyer Design

Beyond the fact that every living thing capable of sentient navigation employs flapping wings for sustained aerial locomotion, certain features of flapping wing flight make it attractive for those missions in which MicroFlyers are believed to have the greatest potential.

Why Flapping Wing Flight?

If the most justifiable missions for MicroFlyers are indoors, then a vehicle must be optimized to negotiate constricted spaces that are bounded on all sides, land and take off with minimal ground roll, and circumvent obstacles (e.g., doors). Fixed wing solutions are immediately discounted because they require either high forward speed, large wings, or a method for creating circulation over the wings in the absence of fuselage translation.

High speed is not conducive to indoor operations because it results in reduced reaction time, especially when autonomously navigating through unbriefed corridors or amid obstacles. When indoors, slower is better.

If, on the other hand, the wings are enlarged to decrease wing loading to accommodate slower flight, the vehicle soon loses its distinction as a "micro" air vehicle. Current wisdom defines a micro air vehicle as having no dimension greater than 15 cm. Even at this scale, the forward speed required for a fixed wing vehicle to efficiently stay aloft violates the criteria for negotiating constricted spaces..

Finally, there are methods for creating circulation over the wings in the absence of fuselage translation. This can be done by "blowing" the surfaces of the wing to increase lift in an intelligent manner by using an internally-generated pressure source. This has been demonstrated in manned aircraft and certain experimental unmanned vehicles, but is typically inefficient unless there is a source of gas pressure already available (such as bleed air from a gas turbine engine).

Another way to move air over a wing without fuselage translation is to move the wing relative to the fuselage and the surrounding air. This can be a circular motion as in a helicopter rotor, or it can be a reciprocating motion as in a flapping wing. Both serve to create a relative wind over an airfoil thereby creating lift.

A rotor is mechanically simple to spin, but does not use all parts of the wing (rotor) with the same efficiency since the inner section near the rotor hub moves more slowly than the tip. The same thing can be said for a flapping wing where the greatest relative wind is created at the wing tip, and none at the root.

A significant advantage of a flapping wing over a rotor is the rigidity of the wider chord wing relative to the high aspect ratio of a narrow rotor blade, and the fact that it can be fixed relative to the fuselage (e.g., nonflapping glide) to reclaim potential energy more efficiently than an autorotating rotor.

It could also be argued that a flapping wing implementation is an inherently lower bandwidth system than one using a helicopter rotor. Both systems require cyclic (once-per-flap or once-per-revolution) control inputs to maintain vertical lift and stability, but the frequencies at which these inputs must be generated can be much lower for comparably sized flapping implementations.

There is also a stealth advantage of a flapping implementation over a comparably sized rotor design in that the acoustic signature will be less because the average audible energy imparted to the surrounding air by the beating wing is much less than that of a rotor. The amplitude of vortices shed from the tips of the beating wing grows, and then diminishes to zero as the wing goes through its cyclical beat, whereas the rotor tip vortices (which are the primary high frequency sound generator) are constant and of higher local energy. The sound spectrum of a flapping wing will be distributed over a wider frequency band with less energy occurring at any particular frequency, thereby making it less noticeable to the human ear. All the energy of the rotor spectrum will be concentrated in a narrow band that is proportional to the constant rotor tip velocity.

As the diameter of a rotor system decreases with the size of the air vehicle design, it will become less efficient since the velocity at the tips will decrease while the useless center portion becomes a larger percentage of the entire rotor disk. To compensate for this, the designer will tend to increase the rotation frequency of the rotor to maintain lift for a given fuselage mass and power source. The increased rotation frequency will increase the frequency and energy content of the sound produced.

On the other hand, as the wing span of a flapping wing system is decreased, wing beat frequency must similarly be increased to maintain lift for a given fuselage mass, but the spectrum of the sound produced will simply broaden with more energy occurring at higher frequencies. Though the work produced to lift the fuselage mass may be the same as that for the rotorcraft, the energy will be expended over a wider acoustic bandwidth, but unlike the rotorcraft, it will be nonuniformly distributed in the horizontal plane. The net result is that a any flapping wing approach will be less noticeable than a rotary wing approach because the sound spectrum produced will approximate wide band white noise rather than a discrete tone.

The flapping wing is conducive to slow flight and even hover. It allows for short take off and landing, and may have advantages over other techniques in terms of its acoustic signature. All of these features are desirable for indoor operations, but what about circumvention of obstacles such as doors? None of the techniques mentioned so far has any particular advantage when it comes to movement through small openings such as partially-opened doors or under closed doors. Similar problems exist for small openings like windows, air vents, and pipes.

The solution is to have a multimode vehicle that is capable of not only flight, but ground locomotion. Crawling is not a particularly efficient form of locomotion if large distances must be traversed, but a machine capable of only flight is effectively neutralized were it to encounter a closed door. If a flying machine could drop to the floor and crawl the small distance necessary to go under the door, then the mission could continue.

The notion of a hovering "humming birdlike" sensor platform that darts about a room inspecting different items of interest, is constrained in the near term by the energy density of its power source. Until greater power densities can be achieved, the likely mode of operation will entail a covert quick entry to a distant area using flight, followed by a precise positioning of a sensor using ground locomotion. This may represent one percent of the overall mission duration. The remaining ninety nine percent will revolve around the operation of the emplaced sensor from its remote vantage point.

Power to Fly

The power necessary to achieve flapping flight can be calculated by using formulas derived by Azuma[2], 1992. This power is mainly a function of the following variables: vehicle mass, flapping frequency, forward speed, wing chord, wing span, and wing beat amplitude. Calculations for a slow flying flapping wing vehicle weighing 50g have been estimated (Michelson[4], 1997). Based on this analysis, just over a watt of power would be necessary to propel such an MicroFlyer. Weight reduction is the most critical factor in creating a successful MicroFlyer. The equations of flight contain terms in which weight contributes to the fourth power. Note that a doubling the MAR mass from 50g to 100g results in almost eight times the required power. For this reason it is critical that MAR structures serve multiple purposes. As an example, wings could also be antennas, legs could be inertial stabilizers in flight—perhaps someday the fuselage might even be itself a consumable fuel source!

Present State-of-the-Art in Aerial Robots

Though work is currently underway to develop fully autonomous MicroFlyers capable of indoor operations early in the 21st century using seek/avoid navigation strategies, the smallest most intelligent fully autonomous robots are currently those found in the International Aerial Robotics Competition. These aerial robots are less than 3 meters (10 feet) in any dimension and are fully autonomous. Since the inception of the competition in 1990, collegiate teams from around the world have devised autonomously navigating aerial robots capable of perceiving their environment, moving intelligently over an arena, and manipulating objects on the ground while in flight. Some of these automatons replan their routes based on the information about what they sense on the ground. A recent mission required the aerial robots to find a toxic waste dump, map the location of randomly oriented, partially buried drums, then read the labels on the drums from the air to determine the contents of each, and having done so, retrieve a sample from a particular drum. This mission was achieved in 1997 by a fully autonomous flying robot which was self navigating for nearly 20 minutes [http://avdil.gtri.gatech.edu/AUVS/IARCLaunchPoint.html].

Potential Applications

Autonomous robots will be necessary for applications which are too dull, dirty, or dangerous for human beings, or for missions which extend beyond a human life span such as space travel. These mobile robots will autonomously navigate the planet's surface, oceans, and skies without human intervention, albeit with assistance from navigation aids such as GPS which will take on greater importance as mobile robots proliferate throughout society. Future applications will include automated delivery services, continuous high altitude in situ weather measurement, service robots to maintain our living space, autonomous farming machinery, personnel transports, and of course the most effective and terrifying machines of war ever to be devised.

Prospects

Many robots exhibit levels of autonomous navigation. The simplest of which follow straight line headings to a target such as the navigation system used by the Nazis on the V1 "buzz bomb". Others are capable of autonomous preprogrammed waypoint navigation such as the Tomahawk cruise missiles used during the Gulf War of 1990. Still others like those of the International Aerial Robotics Competition are thinking machines capable of planning a route and autonomously navigating to a goal while monitoring external cues to execute en route path modifications if necessary. As the level of onboard intelligence increases with increasing computing power, the ability to navigate autonomously will become more common in mobile robots of all types. During the 21st century one should expect to see the end of teleoperated robotic control in favor of fully autonomous operation.

Conclusions

MicroFlyers are best suited to indoor missions because the environment is benign and no other assets exist to address this area of reconnaissance. Indoor operations will have to be autonomous due to

MicroFlyer size constraints that prevent it from carrying various non-scaling items such as lower frequency transmission systems. Also, command and control information can not be sent through most steel-reinforced concrete buildings with the required bandwidth to allow for teleoperation of the vehicle.

When operating autonomously indoors, MicroFlyers will have to be more than "air vehicles", they will have to be "aerial robots" capable of multimode locomotion that will include not only flight but crawling. When in flight, they will have to be able to move slow enough to negotiate winding corridors, stairwells, and narrow openings. Slow flight for unobtrusive reconnaissance missions is best done with flapping-wing propulsors.

Near term propulsion for tiny multimode robotic vehicles will be fueled from chemical or fossil fuel sources. Electrical storage density is insufficient to support slow-flight missions of reasonable endurance at this time. A reciprocating chemical muscle has been developed and tested at a macro- and milli-scale for use in a flying/crawling mechanical insect ("entomopter") referred to as a Mesoscaled Aerial Robot. The MAR uses a novel X-wing pair design that is resonantly driven by the reciprocating chemical muscle.

Empirical tests on a third generation milli-scaled reciprocating chemical muscle show that it develops sufficient force and motion to drive the wings of the MAR at frequencies necessary for flight. The characteristics of the reciprocating chemical muscle comport with those of insects, though currently at a larger "milli scale". In particular, a muscle extension/contraction range of almost 30 percent of the overall muscle length (far exceeding that of most insect muscles which are on the order of 1.5 percent) has been demonstrated at a reciprocating frequency exceeding 70 Hz and a force available of 525 grams (1.16 lbs) over the entire range of motion.

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Missions and Design Criteria

Wednesday 15 September 1999

14.00 - 15.30 (1.5 hours) **MicroFlyers and Aerial Robots:** ***Missions and Design Criteria***
Prof. R. C. Michelson, Georgia Inst. of Technology, USA

AERIAL ROBOTICS

LEVELS OF AUTONOMY/INTELLIGENCE

RPV vs. UAV, is there a distinction?

Remotely Piloted
Radio-Controlled LOS Visual Feedback
No Onboard Sensory Feedback
Example: Model Airplanes

Teleoperation (virtual reality)
Onboard Real-Time Vision Sensor Feedback *(Definitely)*
Real-Time Control Force Feedback *(maybe)*
Onboard Real-Time Sound Sensor Feedback *(maybe)*
Example: Pointer

Teleoperation with Preprogrammed Flight Modes
Automated Modes
On-Board Real-time sensory feedback may be present
Example: V1 "Buzz-Bomb", Pioneer

Waypoint Navigation (Dead Reckoning)
On-Board Sensory Feedback not Necessary in Real time
Example: CL-287

Directed Autonomy (semi-autonomous)
On-Board Real-Time Sensory Feedback not Necessary at all times
Example: Mars rover, IARC vehicles

Fully Autonomous (sentient machine or biological intelligence)
On-Board Sensory Feedback Never Necessary
Example: Imperial Probe Droids, Biological UAVs
(bats and carrier pigeons)

INTERNATIONAL AERIAL ROBOTICS COMPETITION (IARC)

The Millennial Event (11:05 film)

Off-Board vs. On-Board Intelligence

Advantages of Off-Board Intelligence

LESS WEIGHT TO CARRY
- Less Power Required *(weight)*
- Longer Mission *(more fuel)*

LOWER COST AIR VEHICLE *(and System in general)*

COMPUTING POWER (beyond the state-of-the-art in miniaturization)

Advantages of On-Board Intelligence

FREEDOM FROM LINKS
- Greater Radius of Operation
- Jam Resistance
- Stealth
- Higher Degree of Interoperability
- Not Link-Bandwidth Limited
- Not link-latency Limited

QUICKER REACTION TO INTERNAL/EXTERNAL THREATS

SELF NAVIGATION

INNATE SITUATIONAL AWARENESS

15.30 - 16.00 (0.5 hours) **BREAK**

16.00 - 17.30 (1.5 hours) **MicroFlyers and Aerial Robots:** ***Missions and Design Criteria*** (continued)

Prof. R. C. Michelson

Sensors

Payloads vs. Avionics

Some Sensor Types

ATTITUDE
- Accelerometer
- Rate Gyro
- Vertical Gyro
- Ground Contact
- Magnetic and Radio Heading

POSITION
- Barometric Pressure *(Density altitude)*
- Electromagnetic Altimeters
- Pitostatic Pressure *(air speed)*
- Proximity

NAVIGATION
- Navigation Aids *(INS, DGPS, LORAN, Scene Recognition)*
- Kalman Filter Predictors
- Route Planners
- Distance Measuring Equipment

HEALTH
- Computational Integrity *(redundancy/coding)*
- Engine Health Sensors *(temp/pressure/etc.)*
- Air frame Health Sensors *(vibration/fatigue)*
- Available Energy *(fuel/battery)*
- BIT

FEEDBACK
- Actuator Position (linear/angular)
- Component RPM

MISSIONS AUTONOMOUS AERIAL ROBOTS

MILITARY/FEDERAL GOVERNMENT

Lethal

- Unstoppable Machines of War *("Terminator")*
- Aerial Mines

Nonlethal

- NBC Operations
- Hazardous Waste *(e.g., inspection/mapping/remediation)*
- Perimeter Sentry
- Reconnaissance
- Low altitude "satellite" /repeater/jammer

CIVIL

Municipal

- Traffic Surveillance
- Utilities *(e.g., power line inspection)*
- Police
- Search and Rescue
- Air quality sampling
- Low altitude "satellite" /repeater

Private

- Real Estate
- Legal/Insurance *(standoff reconnaissance)*
- Agricultural *(e.g., forestry/farming reconnaissance)*
- Package delivery *(e.g., transPacific, transarctic)*

MISSIONS SPECIFICALLY FOR AUTONOMOUS MICROFLYERS

MILITARY/FEDERAL GOVERNMENT

Lethal

- Targeted Individuals *(assassinations)*

Disruption

- Flying Swarms *(e.g., aircraft interference)*
- Clinging Swarms *(e.g., antenna blocking/mismatching)*
- Targeted equipment

Nonlethal

- Secured Perimeter Penetration
- Indoor Reconnaissance *(e.g., espionage)*
- Covert Reconnaissance
- Relay
- Covert delivery
- "Over the Next Hill Reconnaissance"??

CIVIL

Municipal

- Utilities *(e.g., inaccessible locations, nuclear plants)*
- Police
- Search and Rescue *(Oklahoma bombing, Izmit earthquake)*
- Air quality sampling *(inside smoke stacks)*

Private

- Toys
- Agricultural
- Legal/Insurance *(invasive reconnaissance)*

17.30 Conclude for Wednesday

Thursday 16 September 1999

09.00 - 10.00 (1.0 hours) **Microflyers and Aerial Robots:** ***Missions and Design Criteria*** (continued)
Prof. R. C. Michelson

MICROFLYER DESIGN CRITERIA

What are MicroFlyers or Micro Air Vehicles?
What is the *REAL* Mission for MicroFlyers?
What are the Technology Hurdles?
The "Big Three"
- Non-scaling Items
- Energy Storage and
- Propulsion

Conclusion: Navigation must be Autonomous
How to Navigate Autonomously
Indoor Flight Mechanisms
Fixed Wing?
Rotary Wing?
Flapping Wing?
Power Necessary to Fly... the beginning design point
Electrical vs. Chemical
Reciprocating Chemical Muscle
- *(RCM film)*

Weight is our Enemy!
Efficiency through Multifunctionality
DARPA Micro Air Vehicle Program Objectives *(revisited)*
DARPA Mesoscaled Aerial Robot Program Objectives
MAR Design Criteria
Innovative "Twist" on Flapping Wing Flight
- *(X-wing+Resonance+Slow Flight film)*

Innovative Flight Control Mechanism
Innovations in Wing Fabrication

10.00 Thursday Morning Lecture Concludes

For Additional Information, Consult the Following Sources:

1. **International Aerial Robotics Competition**
   .... http://avdil.gtri.gatech.edu/AUVS/IARCLaunchPoint.html
2. **Current International Aerial Robotics Competition Mission**
   .... http://avdil.gtri.gatech.edu/AUVS/CurrentIARC/FutureEventInfo.html
3. ***Dragon Stalker*** **Development**
   .... http://avdil.gtri.gatech.edu/RCM/RCM/DroneProject.html
5. **Mesoscaled Aerial Robot**
   .... http://avdil.gtri.gatech.edu/RCM/RCM/Entomopter/EntomopterProject.html
6. **About the Presenter**
   .... http://avdil.gtri.gatech.edu/RCM/RCM/MICHELSON.bio.html

MicroFlyers and Aerial Robots: ***Missions and Design Criteria***

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